

CERN-TH/98-377

hep-ph/9812231

On the photon constituency of protons

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Abstract

We argue that existing measurements of ep collisions at HERA –in which an energetic photon is made via a QED ‘Compton’ subprocess– can provide rather detailed information on the photonic parton density of the proton. This function and its deviations from Bjorken scaling should be measurable, allowing for an interesting test of the theory. The photonic distribution function and its gluonic counterpart should show a strikingly different evolution with momentum scale.

CERN-TH/98-377

November 1998

arXiv:hep-ph/9812231v1 2 Dec 1998

1 Introduction

The ep collisions in which there is an energetic photon in the final state can be classified according to their distinctive kinematical features. We are concerned in this note with the Compton subprocess $e\gamma \rightarrow e\gamma$, where the initial photon is coupled to the proton and is (almost) on-shell. Progress at HERA [1] and the subsequent prospects for improved measurements induce us to revisit, update and extend earlier theoretical work on this subject [2]–[6].

Figure 1 shows the lowest-order ‘Compton’ Feynman diagrams, along with our notation for the kinematical variables. At the HERA collider, events of this type have a particularly clean and distinctive signature, as there are only an electron¹ and a photon in the final state, with little or even no observable hadronic activity. In addition, to lowest order in perturbation theory, the (large) transverse momenta of the electron and the photon approximately balance each other. Conversely, applying these distinctive features as selection criteria allows one to extract, to the leading log approximation, Compton events from the ensemble of radiative corrections [7].

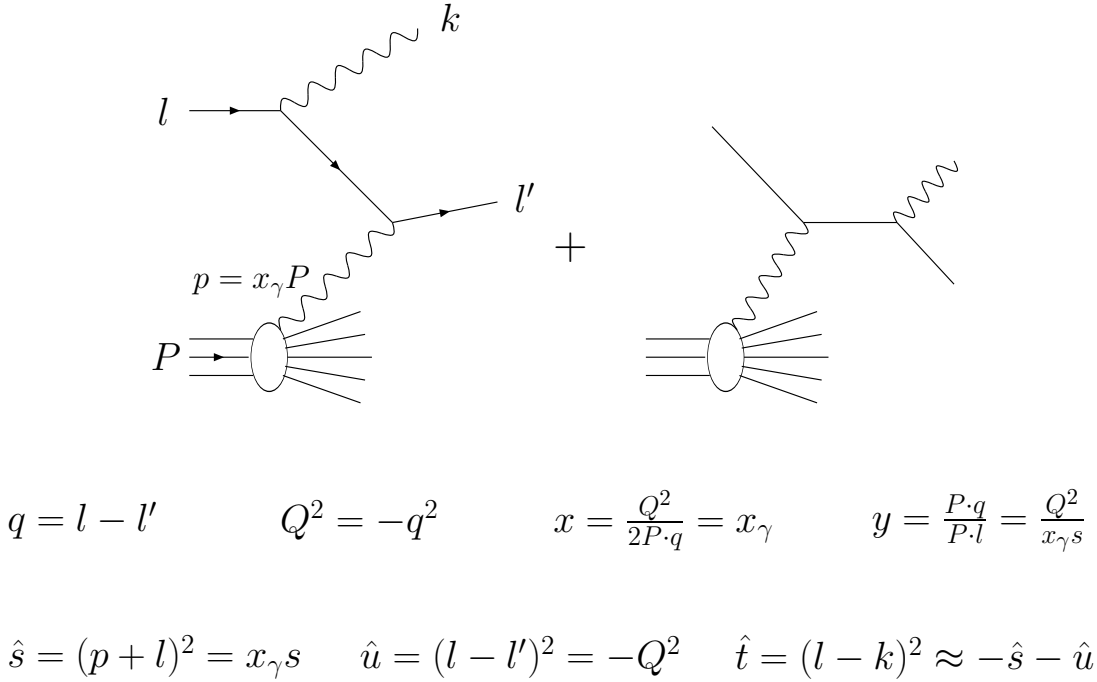


Figure 1: Lowest-order Feynman diagrams for Compton scattering in ep collisions.

We are interested in the $ep \rightarrow e\gamma X$ Compton process at relatively large momentum scales Q^2 ; we refer to it as Deep Inelastic Compton Scattering (DICS). The

¹We call both electrons and positrons ‘electrons’.

experimental study of DICS at HERA offers the unique possibility of measuring the photon-parton content of the proton and the corresponding longitudinal-momentum distribution or ‘structure’ function $\gamma(x, Q^2)$. In the ‘parton model’ approximation in which the initial photon is on-shell and collinear with the proton, the relation between the DICS differential cross section and $\gamma(x, Q^2)$ is [4]:

$$\frac{d^2\sigma(s, x, y)}{dx dQ^2} = \int_x^1 \frac{dz}{z} \frac{d^2\hat{\sigma}^{e\gamma \rightarrow e\gamma}(xs, x/z, y)}{d(x/z) dQ^2} \gamma(z, Q^2), \quad (1)$$

where

$$\frac{d^2\hat{\sigma}^{e\gamma \rightarrow e\gamma}(\hat{s}, \hat{x}, y)}{d\hat{x} dQ^2} = \frac{2\pi\alpha_{em}^2}{\hat{s}^2} \frac{1 + (1 - y)^2}{1 - y} \delta(1 - \hat{x}). \quad (2)$$

A measurement of $\gamma(x, Q^2)$ would acquire particular interest when compared with that of its non-Abelian counterpart: the gluon distribution function $g(x, Q^2)$. The predictable Q^2 evolution of these functions ought to be very different, their difference representing a very clean test of the non-Abelian nature of the gluon. More specifically, the self-coupling of gluons makes $g(x, Q^2)$ evolve with Q^2 , at small x , much faster than $\gamma(x, Q^2)$. The evolution of $\gamma(x, Q^2)$ with Q^2 is by itself an interesting test of the QCD-based parton picture, which we argue can be performed at HERA with the existing or soon to be gathered statistics.

One can in principle, and sometimes in practice, distinguish two types of contributions to DICS: ‘pseudo-elastic’ $ep \rightarrow e\gamma p$, and ‘inelastic’ $ep \rightarrow e\gamma X$ with $X \neq p$. From a parton model point of view, in which the struck photon in Fig. 1 is viewed as a proton constituent, the distinction between pseudo-elastic and inelastic subprocesses is very artificial. This is best understood by comparing conventional deep inelastic scattering with the Compton process, as we do in Fig. 2. Deep inelastic scattering, Fig. 2a, results in two final-state jets: the ‘current’ or struck quark jet and the ‘spectator’ jet of target fragments. The invariant masses of these jets (to the extent that they can be ascertained without ambiguity) are small; the unavoidable colour reconnection between the struck quark and the target fragments is in general a soft process. At high Q^2 a successful recombination leading to an elastic event $ep \rightarrow ep$ is a rare occurrence. Similarly, the photon and the target fragments in the Compton process of Fig. 2b would even more rarely recombine into a proton, to result in a literally elastic scattering event $ep \rightarrow ep$. There is nothing very special about the ‘pseudo-elastic’ $ep \rightarrow e\gamma p$ channel, which ought to be quite common, since the invariant mass distribution of the target fragments will, as in deep inelastic scattering, tend to be low. In DICS the total invariant mass of the proton’s fragments (the hadrons as well as the outgoing photon) will, again as in deep inelastic scattering, be large in general.

The pseudo-elastic contribution to DICS can be easily worked out in terms of measured proton form factors [2]. In the current state of our understanding of QCD, it is simply impossible to predict the contribution of final hadronic states of invariant mass $W_H > m_p$. To study the feasibility of measuring $\gamma(x, Q^2)$ and its Q^2 evolution in DICS we must, as other authors [3]–[6] have done before us, proceed

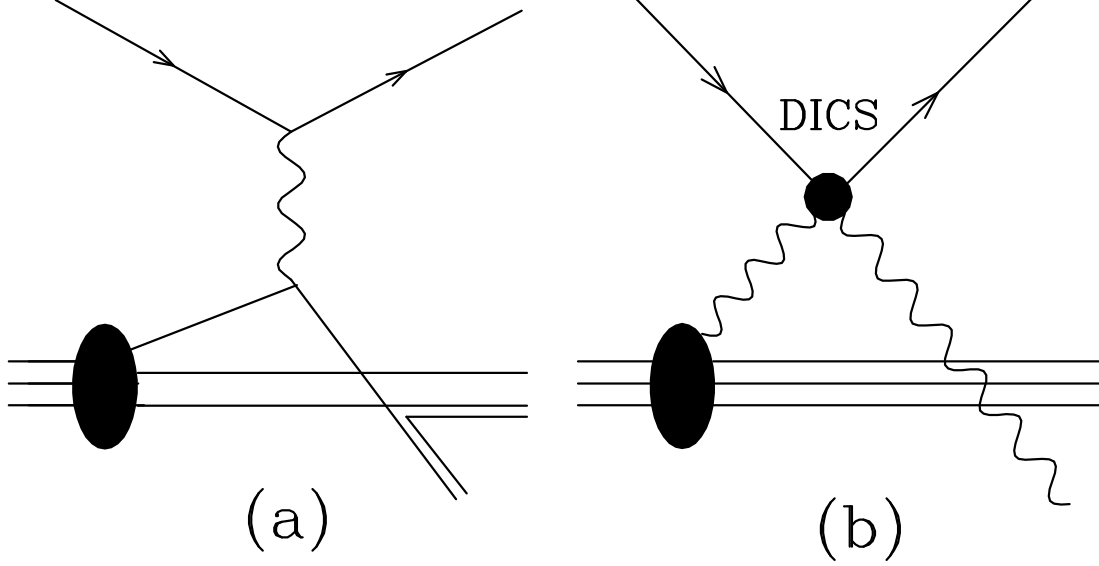


Figure 2: Diagrams for deep inelastic conventional and ‘Compton’ scattering.

to make a series of conjectures. Mercifully, these conjectures are not relevant to the Q^2 evolution, which is a solid prediction of the standard model.

2 Pseudo-elastic DICS

The contribution of the pseudo-elastic channel $ep \rightarrow ep\gamma$ to $\gamma(x, Q^2)$ can be explicitly written down in terms of the proton’s elastic form factors [2]. The usual ‘electric’ and ‘magnetic’ form factors are empirically well fit as dipoles:

$$G_E(t) \simeq \frac{1}{[1 - t/(0.71 \text{ GeV}^2)]^2}, \quad G_M(t) \simeq 2.79 G_E(t). \quad (3)$$

Define the quantities:

$$H_1(t) \equiv \frac{G_E^2(t) - (t/4m_p^2)G_M^2(t)}{1 - t/4m_p^2}, \quad H_2(t) \equiv G_M^2(t), \quad (4)$$

to express the pseudo-elastic contribution to $\gamma(x, Q^2)$ as:

$$\gamma_{el}(x) = -\frac{\alpha_{em}}{2\pi} x \int_{t_1}^{t_2} \frac{dt}{t} \left\{ 2 \left[\frac{1}{x} \left(\frac{1}{x} - 1 \right) + \frac{m_p^2}{t} \right] H_1(t) + H_2(t) \right\}, \quad (5)$$

where the limits on the virtual photon mass t are:

$$t_{1,2} = 2m_p^2 - \frac{1}{2s} \left[(s + m_p^2)(s[1 - x] + m_p^2) \pm (s - m_p^2) \sqrt{(s[1 - x] + m_p^2)^2 - 4sm_p^2} \right]. \quad (6)$$

The tempting analogy between photons and gluons as partons in the proton breaks down at various points. One of them is that colour confinement and conservation preclude the existence of a strict coloured analogue to a quasi-elastic channel: there are no QCD elastic form factors. A neutral and spinless hadron, such as a K_L , would have a very small quasi-elastic contribution to its photonic structure function $\gamma_K(x, Q^2)$, satisfying in this respect a QED/QCD analogy more closely than a proton does. But the proton carries a long-range photon field and $\gamma_{el}(x)$ is an important contribution to its $\gamma(x, Q^2)$. Another departure from the photon/gluon analogy is that, in DICS, it is justified to work to leading order in α_{em} , and to this order the quantity $\gamma_{el}(x)$ of Eq. (5) is independent of Q^2 .

At an ep collider, a separation of elastic and inelastic Compton events is difficult but possible. A fraction of elastic events could be tagged by the very forward ‘diffraction’ detectors. Inelastic events with proton fragments at sufficiently large p_T could be caught by larger-angle detectors. Although the elastic contribution can be ascertained with accuracy, we see no particular interest in singling it out experimentally except, perhaps, as a calibration and/or luminosity check [1].

3 Inelastic DICS

In principle one could build-up the complete function $\gamma(x, Q^2)$ by adding to the quasi-elastic contribution all resonant [5] and non-resonant final hadronic states, and their interferences. Alternatively one could directly guess, one way or another, an inclusive or ‘continuous’ non-elastic part of $\gamma(x, Q^2)$. If this guess is based on a parton picture wherein the photon ‘constituent’ is emitted by one of the quarks in the proton [3, 4, 6], the addition of the continuous and resonant contributions may be double-counting, as it would certainly be in e^+e^- annihilation [8] and arguably be in deep-inelastic scattering [9]. In these latter cases the data provide the decisive proof that there is a ‘duality’ between continuous and resonant contributions: adding them is double-counting. In DICS, the information on $\gamma(x, Q^2)$ is at the moment too sparse to help decide on this interesting question.

Having to make a guess, we choose to make one that is correct in that aspect of $\gamma(x, Q^2)$ for which the QCD prediction is unequivocal: the Q^2 evolution. Two diagrams for the contribution of quark–gluon scattering to high- p_T photon production are shown in Fig. 3. Notice that, with the substitution of gluons for photons and of a parton–quark for an electron, they are identical to the Compton diagrams of Fig. 1. This implies that DICS is ‘factorizable’ in the same sense as ‘Drell–Yan’ scattering or the production of high- p_T photons or jets in hadronic collisions [10]. In turn, this means that $\gamma(x, Q^2)$ satisfies a ‘QED evolution’ equation [11]. To lowest

order in α_{em} and α_s [6], and in an obvious notation²:

$$\frac{d\gamma(x, Q^2)}{d \ln Q^2} = \frac{\alpha_{em}}{2\pi} \int_x^1 \frac{dy}{y} \sum_q e_q^2 P_{Aq} \left(\frac{x}{y} \right) \left[q(y, Q^2) + \bar{q}(y, Q^2) \right], \quad (7)$$

where the quark-to-gauge-boson splitting function is:

$$P_{Aq}(z) = \frac{1 + (1 - z)^2}{z}. \quad (8)$$

A function $\gamma(x, Q^2)$ satisfying Eq. (7) is automatically correct to the leading logarithmic order in QED. This is also the order to which it is permissible to single out Compton scattering from the other radiative processes in ep collisions.

We have chosen the lepton-to-lepton squared momentum transfer Q^2 as the scale in Eq. (7). A scale $p_T^2(e, \gamma)$ or either of the quantities \hat{s} , $-\hat{t}$ defined in Fig. 1 would be equally reasonable. To leading order of perturbation theory there is no way to favour any particular choice.

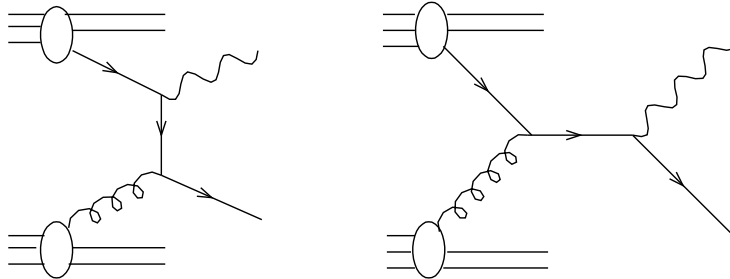


Figure 3: Quark-gluon scattering in high- p_T γ production in pp collisions.

The non-Abelian generalization of Eq. (7) is the gluon-evolution equation [12]:

$$\frac{dg(x, Q^2)}{d \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dy}{y} \left[\sum_q \frac{4}{3} P_{Aq} \left(\frac{x}{y} \right) \left[q(y, Q^2) + \bar{q}(y, Q^2) \right] + P_{gg} \left(\frac{x}{y} \right) g(y, Q^2) \right], \quad (9)$$

where the (lowest-order) gluon-to-gluon splitting function P_{gg} is given in [12]. An interesting challenge to experiment is to observe the different Q^2 evolutions of γ and g , as predicted in Eqs.(7) and (9).

To illustrate the experimental feasibility of a measurement of $\gamma(x, Q^2)$ and its evolution, we must guess that function explicitly. For the guess to be consistent with QCD, it must be compatible with Eq. (7). We follow [6] in writing $\gamma = \gamma_{el} + \gamma_{in}$ and figuring out $\gamma_{in}(x, Q^2)$ by evolving an input $\gamma_{in}(x, Q_0^2)$ with the use of Eq. (7). We also follow [6] in assuming that γ_{in} vanishes at a low $Q_0 = 0.5 \text{ GeV}$; it builds up at

²The $O(\alpha_{em})$ modifications of the quark and gluon evolutions induced by a non-vanishing $\gamma(x, Q^2)$, affect the evolution of the latter only at $O(\alpha_{em}^2)$.

$Q^2 > Q_0^2$ via evolution. This is admittedly as arbitrary for a photon constituency as it would be for its gluon counterpart; the proton being a bound state of charged coloured objects, there is no reason for it to be ‘made’ of only quarks at any scale, even at leading twist and leading order of perturbation theory. We differ from [6] in our use of a more recent set [13] of parton densities³.

We deal with momentum scales comparable to the proton mass and we should be making target mass-corrections distinguishing Bjorken’s x -scaling [14] from Nachtmann’s ξ -scaling [15]. As it turns out, $\gamma(x, Q^2)$ is only measurable at values of x small enough for this distinction not to be important.

4 Experimental details and expectations

In [1], a first measurement of DICS at HERA was presented; at that time the main aim was the use of Compton events as an independent luminosity monitor. The roughly 400 reported events were insufficient to study differential distributions and to provide a measurement of γ . Moreover, for many of these events it was not possible to tell which of the electromagnetic showers was the electron and which was the photon. Since then, about two orders of magnitude more luminosity have been accumulated. In addition, silicon trackers have been installed in the backward region, and charge identification is now possible with much higher efficiency. We show that, given these improvements, a lot of information on $\gamma(x, Q^2)$ can be extracted from existing data.

To match the experimental situation, we use the following parameters and cuts, the latter akin to the ones used for event selection in the quoted H1 analysis [1]:

- The beam energies are $E_e = 27.5$ GeV and $E_p = 820$ GeV. We slightly over-estimate event rates by using the current value of $\mathcal{L} = 36.5/\text{pb}$ for the total luminosity⁴ collected by H1.
- The electron and the photon are both seen by the central detector, i.e. they have $0.05 \text{ rad} \leq \theta_{e,\gamma} \leq \pi - 0.05 \text{ rad}$ (as usual, angles are measured with respect to the proton beam direction).
- At least one of the electromagnetic clusters has an energy of more than 8 GeV, and both of them have at least 5 GeV. The latter requirement guarantees a high detection efficiency.
- Other cuts in [1] are automatically satisfied at the level of our leading-order calculation. The total visible electromagnetic energy is always larger than 18

³This leads to an increase of the conjectured $\gamma(x, \mu^2)$ at small x , relative to the result in [6].

⁴Our numbers can be easily rescaled to the luminosity collected after the installation of the silicon trackers.

GeV (the final $e + \gamma$ energy equals $E_e + x_\gamma E_p > 27.5$ GeV). Except in the forward region there is no additional (hadronic) cluster with more than 2 GeV energy. The $e\gamma$ acoplanarity angle $\Delta\phi \equiv \pi - |\phi_e - \phi_\gamma|$ is below 45° .

We also demand that no momentum scale be small: for the quantities defined in Fig. 1, $-\hat{t}$, \hat{s} , $Q^2 > 1$ GeV²; for the (equal and opposite) transverse momenta of the final-state electron and photon, $p_T^{e,\gamma} > 1$ GeV.

The first relevant question concerns the number of DICS events, with the quoted integrated HERA luminosity. In Fig. 4 we show, in bins of $\log_{10} x$, the event numbers that survive the above selection criteria. Clearly, they should suffice to measure this x -distribution, a point previously emphasized in [3]–[5]. The electron and photon detection efficiency (and presumably the ability to distinguish them) is high within the applied cuts. We shall thus estimate the statistical errors as the square root of the event number per bin. To measure x , e/γ identification is unnecessary, since $x = x_\gamma$ may be determined from the requirement that the sum of the energies of the two electromagnetic clusters be equal to the combination $E_e + x_\gamma E_p$. Contrawise, for the determination of Q^2 , an e/γ distinction is indispensable.

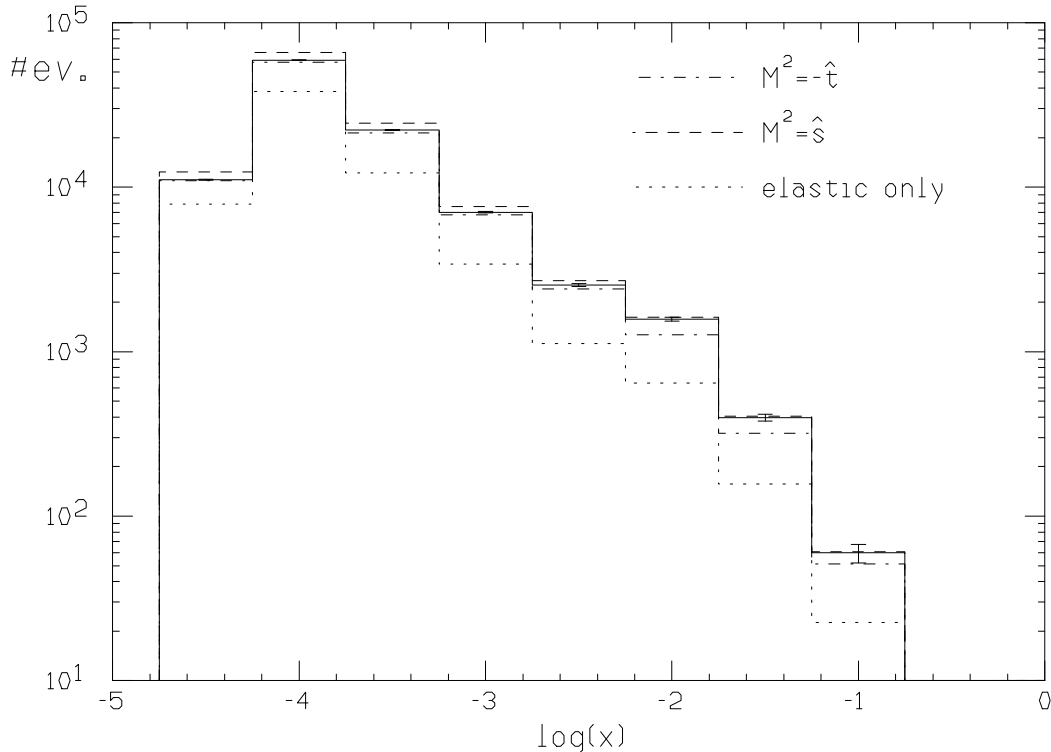


Figure 4: Event rates for the DICS at HERA. The cuts applied are as described in the text. The lowest- x bin contains all events with $\log_{10}(x) \leq -4.25$.

In Fig. 4 the dashed (dash-dotted) histogram depicts the number of DICS events found by integration of Eq. (7) using a scale \hat{s} ($-\hat{t}$) instead of Q^2 . The scale

dependence is a substantial theoretical uncertainty, but is not devastatingly large. The fact that the elastic part is scale-independent helps make the total theoretical expectation fairly stable. The dotted histogram in Fig. 4 shows the event rates predicted on the basis of quasi-elastic scattering only: $\gamma = \gamma_{el}$. It should be an easy task for experiment to confirm, or infirm, the existence of the substantial inelastic contribution that we foretell.

To illustrate the experimental extraction of $\gamma(x, Q^2)$ we translate the information in Fig. 4 into a statement on the accuracy of the measurement. To this end, we evaluate $\gamma(x, Q^2)$ at the statistical averages $\langle x \rangle, \langle Q^2 \rangle$ determined from the event sample used in Fig. 4. We assume that in each bin the error in γ is only statistical. The result for $x\gamma/\alpha_{em}$ as a function of $\log_{10}(x)$ is shown in Fig. 5. For comparison, we also show the contribution of γ_{el} . In practice a possible method [16] to translate the data into a measurement of γ is based on the bin-by-bin evaluation and subsequent iteration of the expression:

$$\gamma^{meas}[\langle x \rangle, \langle Q^2 \rangle] \equiv \frac{\#ev., \text{ data}}{\#ev., \text{ MC}[\gamma^{toy}]} \cdot \gamma^{toy}[\langle x \rangle, \langle Q^2 \rangle], \quad (10)$$

where $\#ev., \text{ MC}[\gamma^{toy}]$ is the expected (theoretical or MonteCarlo) number of events, based on a trial function γ^{toy} . If γ^{toy} is not too far off the true structure function γ , the iteration of Eq. (10) converges fast. A reasonable guess is $\gamma^{toy} \equiv \gamma_{el}$. To see how well this choice works, we make use of it on the right-hand side of Eq. (10), along with our results of Fig. 4 as the ‘data sample’. The $x\gamma^{meas}/\alpha_{em}$ so determined is also shown in Fig. 5. Even this ‘zeroth’ order iteration is accurate.

To study the detectability of the Q^2 dependence of γ , we take the sample used for Figs. 4 and 5 and bin it additionally in Q^2 . The result is shown in Fig. 6. There is an increase of $x\gamma(x, Q^2)/\alpha_{em}$ with Q^2 that should be observable in most x -bins. We also display the Q^2 dependence of the leading-order GRV [13] gluon density, which satisfies Eq. (9). To facilitate the comparison of the relative variations of γ and g , we renormalize $xg(x, Q^2)$ in each subplot so as to coincide with $x\gamma(x, Q^2)/\alpha_{em}$ at the lowest accessible Q^2 . The gluonic function g evolves much more strongly at small x than its photon counterpart γ . Only at $x > 10^{-2}$ does the Q^2 -evolution of γ overtake. The statistics appear to be insufficient to explore in detail the region $x \gtrsim 0.07$, where g starts to decrease with Q^2 , while, for γ , Eq. (7) predicts an increase for all x .

5 Conclusions

We have shown that it is possible to extract $\gamma(x, Q^2)$ –the function describing the photon constituency of protons– from existing data. Even its Q^2 -dependence should be already observable, allowing for an interesting test of a combination of QED and QCD. The photon and gluon distribution functions should show a strikingly different Q^2 evolution.

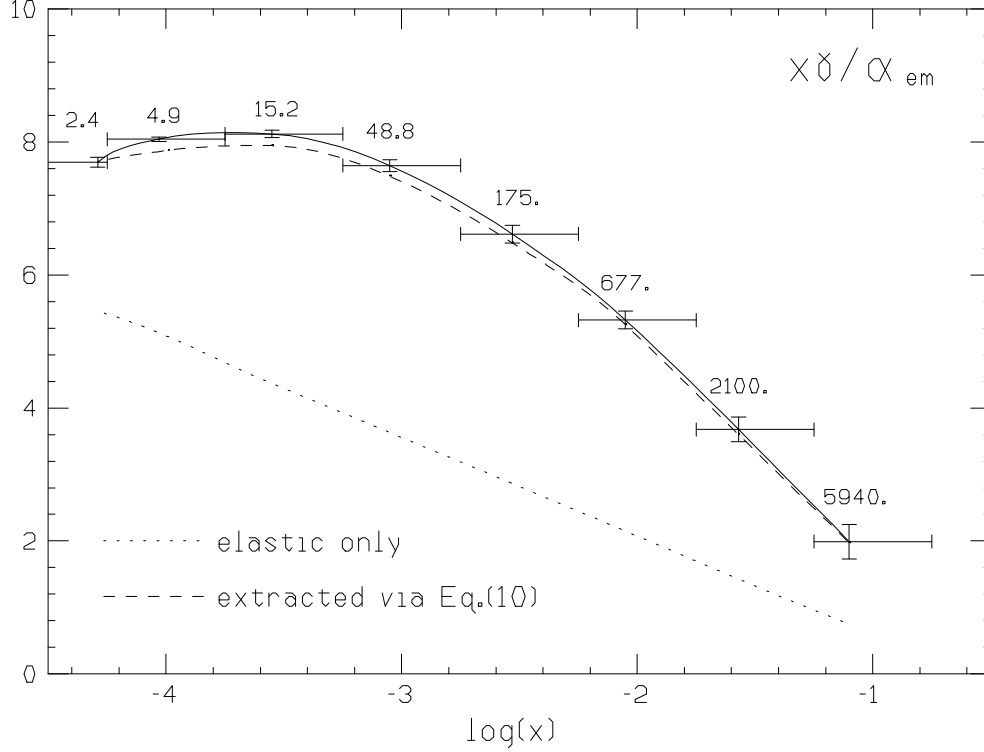


Figure 5: Expected statistical accuracy of the determination of $x\gamma(\langle x\rangle, \langle Q^2\rangle)$. The numbers indicate the average $\langle Q^2\rangle$ (in GeV^2) for each x -bin. The dotted line shows the purely elastic spectrum, while the dashed one corresponds to γ^{meas} ‘extracted’ via Eq. (10) and as explained in the text.

We know so little about the photonic structure function γ that the possible improvements on its theoretical understanding would be premature, since the extra precision they would bring about is surely at a more refined level than the current uncertainty. The corrections to next-to-leading order in α_s would be the most interesting, as they should help control the dependence of the predictions on the choice of variable representing the momentum scale. As measurements of DICS materialize –and we hope they soon will– these improvements should become timely.

Acknowledgements

We are grateful to A. de Roeck for information and many helpful discussions on experimental aspects of the QED Compton process at HERA. We thank A. Vogt for providing the Fortran code for the parton densities of [13]. We also acknowledge useful discussions with G. Altarelli, D. de Florian and M. Stratmann.

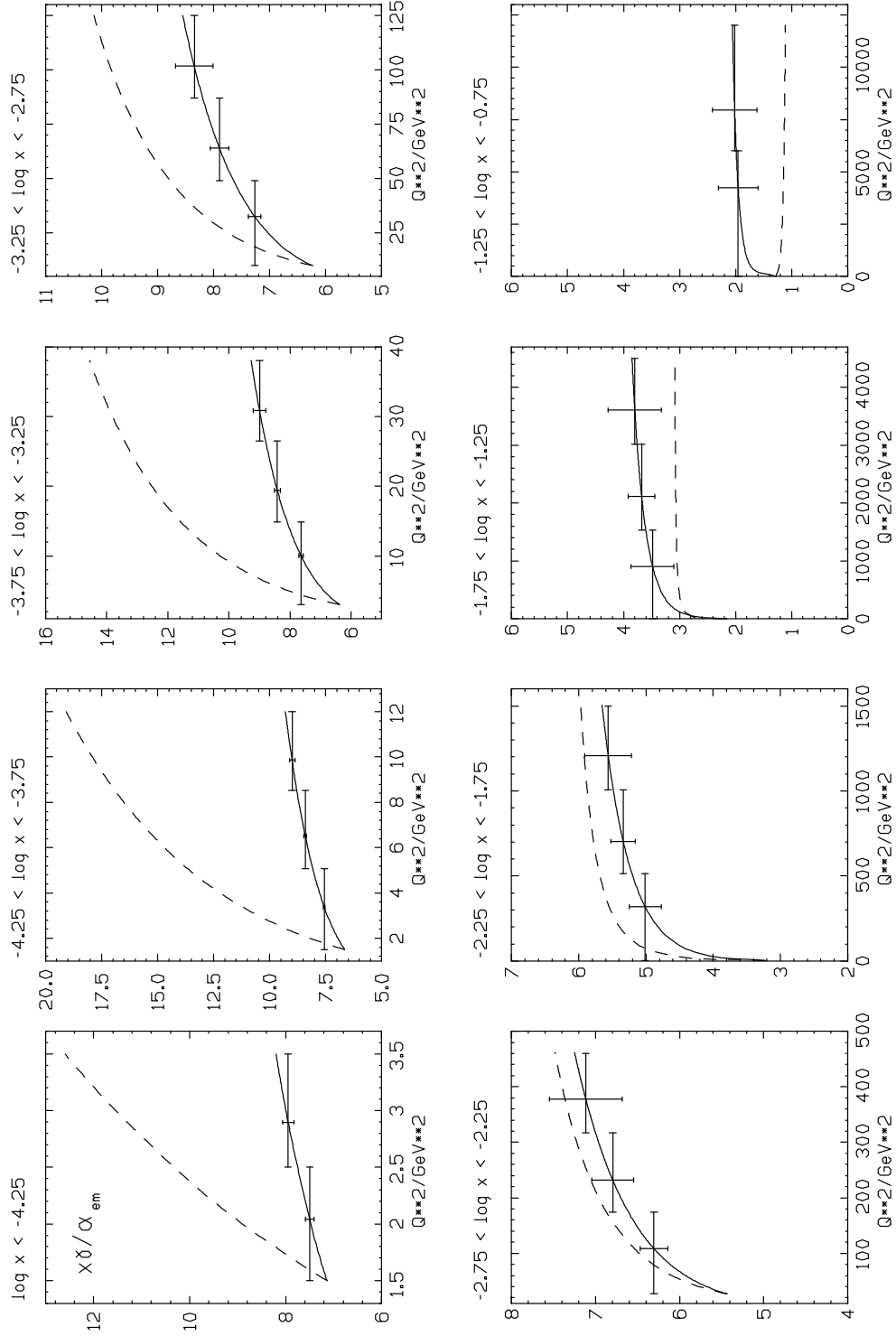


Figure 6: Expected statistical accuracy of a measurement of the Q^2 dependence of $x\gamma(x, Q^2)/\alpha_{em}$ in various x -bins. The dashed line displays the Q^2 dependence of the LO GRV [13] gluon density, which has been normalized in each plot so as to coincide with $x\gamma(x, Q^2)/\alpha_{em}$ at the lowest accessible Q^2 value.

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